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13. ABSTRACT ***(Maximum 200 words)***

This research has focused on the development of a comprehensive mesoscale numerical weather prediction (NWP) system for forecasting clouds anywhere in the world. The host model for performing this research, RAMS, has been extended to a global, interactive nested-grid forecast model that is capable of running on both shared-memory and distributive-memory computers. This unique NWP model is capable of being initialized globally and then being able to telescopically nest anywhere on earth and provide high-resolution 24 to 48h forecasts of clouds and precipitation.

Some of the physical modules developed under support of this project include: a cumulus parameterization scheme designed specifically for use in an interactive-nested grid model, a mesoscale convective system parameterization scheme that interfaces with the cumulus parameterization scheme, a new, computationally-fast, two-moment, stochastic microphysics parameterization scheme, and a new two-stream cloud-radiation model that interfaces directly with the hydrometeor distributions in the microphysics model.

The new cloud forecasting scheme has been tested in applications to Arctic stratus clouds, and mid-latitude and tropical cirrus. The model has been shown to perform very well and moreover, provide new insights into the physics and dynamics of those cloud systems.

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Development and Testing of Physical Algorithms for Cloud Forecasting on the Mesoscale

Grant No. F49620-95-1-0132

To:

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March 18, 1998

1 Introduction

This is the final report for Grant No. F49620-95-1-0132 for the period 15 Jan 95 to 14 Jan 98. The report includes a summary of research progress and an identification of technical transitions which took place. The research focused on the development of physical algorithms and a computational model structure that permits realtime forecasting of clouds and cloud systems anywhere on earth. The target forecasting time scale is 24 to 48 hours.

2 Accomplishments/New/Findings

2.1 The cumulus/mesoscale parameterization scheme

Rafkin (1996) developed a second-generation cumulus parameterization scheme for use in nested-grid models with grid spacings ranging from those typical of general circulation models (GCMs) to mesoscale models with grid spacings as fine as 5 to 10 km. I refer to this as our second-generation system since the first scheme developed by Weissbluth and Cotton (1993) for use in interactive nested-grid models did not perform well for a broad range of convective conditions. It was limited to parameterizing the effects of a single type of cumulus cloud and could thus represent steady deep convection well or smaller towering cumuli but not both in a single model configuration or in a single grid column.

Rafkin's (1996) scheme, on the other hand, can parameterize in a single model configuration or in any grid column, a probability-based ensemble of fair weather cumuli, towering cumuli, ordinary transient cumuli, and long-lived steady cumulonimbi. The scheme is a hybrid mass flux and convective adjustment scheme. The mass flux component resembles the Arakawa-Schubert scheme in which cloud warming and drying are a result of cumulus-induced subsidence and detrainment. The adjustment term has the effect of nudging the grid-averaged properties toward or away from cloud properties depending on whether the sub-cloud-ensemble is expanding or contracting. The convective adjustment term for a particular cloud type or sub-ensemble, becomes dominant as the grid spacing approaches cloud-resolving grids whereas the mass flux component dominates at GCM-type grid spacings. A filter function has been designed to prevent double-counting as the grid spacings become fine enough to allow explicit representation of cloud processes. For grids not large enough to sample the full possible distribution of clouds at any time, a probability density function (PDF) is introduced to define the fraction of a potential cloud ensemble that is actually active within a grid box of limited area. An important feature of the scheme is that the mass flux component uses a relaxed quasi-equilibrium closure in which vertically-integrated cloud kinetic energy for each sub-ensemble is a prognostic variable. This approach is computationally much less demanding than the full quasi-equilibrium closure and adds only two-dimensional arrays to the host model. A complete description and preliminary evaluation of the scheme is described in Rafkin (1996) and in a paper in preparation for submission to a reviewed journal.

The Rafkin cumulus parameterization scheme has been interfaced to a parameterization scheme of mesoscale convective systems (MCSs) (Alexander, 1995; Alexander and Cotton, 1998). The cumulus scheme serves as a driver to the heating and moistening and momentum transports of the stratiform anvil clouds of MCSs. The combination of Rafkin's cumulus scheme and the MCS scheme provide a parameterization of the full range of possible deep convective cloud systems. A filter function is now being designed to prevent double counting

as the grid spacings of large scale models or coarse grid versions of RAMS become fine enough to partially resolve MCS stratiform anvil heating, moistening, momentum transports, and precipitation. The combined cumulus/MCS scheme provides the heating and moistening rates associated with both deep convection and with the large stratiform anvil clouds they produce. Lacking, however, is the issue of when and where to activate this scheme in a host model.

Hongli Jiang has been working on the activation mechanism. The decision to activate the MCS parameterization is based on the evolution of the vertically-integrated total eddy kinetic energy. We propose that total eddy kinetic energy can be partitioned into contributions from the deep cumulus kinetic energy (CKE) and the mesoscale kinetic energy (MKE) associated with the mesoscale circulation branches. Two prognostic equations are then developed for CKE and MKE, respectively. The CKE is generated primarily by convective updrafts and downdrafts, and once generated, CKE dissipates at a specified rate [O(1h)]. The MKE has two fundamental sources. As some of the CKE generated by deep convection dissipates, it converts to MKE as the first source. If sufficient convection is maintained to generate a certain threshold in MKE, then the MCS scheme is activated. Once activated, the second source accounts for further MKE generation due to mesoscale heating, pressure gradient forces, and shear production within the mesoscale circulation branches of MCSs. The sink of MKE is defined as a simple dissipation term with a dissipation rate that is slower than ordinary deep convection [O(5h)].

Several cases of organized MCSs observed during TOGA COARE were selected to tune the coupled cumulus-MCS scheme in a SCM, using observed mean conditions and large-scale forcing as input. Our goal is to generalize the use of the scheme to numerical models covering a wide variety of resolved scale, from GCM to cloud-resolving scales, without any user-defined changes in parameters or algorithms.

2.2 RAMS Two-Moment Bulk Microphysics

The new two-moment, bulk microphysics module evolved from the work of Verlinde et al. (1990) where analytical solutions of the collection equations were derived. Walko et al. (1995) describe the one-moment version of the microphysics where it was found that great computational expedience could be gained by extensive use of lookup tables. Subsequently, Meyers et al. (1997) described the prototype version of the two-moment scheme scheme. Again with the use of many lookup tables this version has been implemented in the main RAMS code. In this module the mixing ratio and number concentration of rain, pristine ice, snow, aggregates, graupel and hail are all prognosed. Cloud water mixing ratio is also prognosed, but the routine for predicting cloud droplet number concentration is still being finalized.

A closed-form, accurate, efficient, non-iterative solution method has been developed to compute heat and vapor diffusion to all hydrometeor categories simultaneously, while at the same time diagnosing potential temperature from ice-liquid potential temperature. This prevents any category from gaining or losing vapor and heat independently without influence (until the next timestep) by or on the other categories. It also replaces the former iterative procedure for computing potential temperature.

Five different habits of ice crystals are represented in the model. The particular habit that occurs at any time and place is diagnosed from local or cloud top temperature and humidity. Previously only one habit was hardwired in the code.

The process of coalescence can produce new hydrometeors having a wide range of properties based on the types and amounts of hydrometeors colliding and on their temperatures. The decision regarding which hydrometeor category the coalesced hydrometeor should be transferred to has been generalized and is more accessible to experimentation.

The processes of melting, evaporation, and shedding of liquid from hail are evaluated in such a way as to represent the size dependence when computing total mixing ratio and number that are transferred from one water category to another.

Supersaturation is now prognosed.

Secondary ice production by splintering of riming cloud droplets has been implemented using a new formulation based on Mossop (1978).

Several changes were made to improve code efficiency, including diagnosing hydrometeor mean mass rather than characteristic diameter as the primary representation of size.

Not fully implemented is the prediction of cloud droplet number concentration , as well as mixing ratio. In this version the source of cloud droplets is directly related to the activation of cloud condensation nuclei (CCN). The sink of cloud droplets is evaporation and stochastic collection.

The number of CCN activated depends primarily on the magnitude of supersaturation, the number of CCN present, the size and chemical properties of CCN, and the number of CCN already activated. Other factors, such as pressure and temperature (independent of their effect on supersaturation) also affect activation.

Three spectra of hygroscopic aerosol are considered, each one characterized by a particular chemistry, mean size, and spectral width. Conservation equations for number concentration is solved for each aerosol species. Initial background concentration and source location and strength are specified from compiled measurements.

The CCN population is not depleted when CCN are activated, but when cloud droplets are collected by rain, ice, or another cloud droplet. This preserves the CCN population for any cloud droplets that simply form, grow by vapor diffusion, and then evaporate.

The number of CCN activated in a model timestep at a given location is given by $CS^k - N$, where N is the number of already activated CCN present at that time and location.

C and k are diagnosed at each time and location as a composite of the type and number of each CCN species present.

S is determined from the computations of a parcel model in which a population of aerosol, represented by the given C and k, are subjected to increasing supersaturation in the same environment as the given time and location in the model. The parcel model computes on a very small timestep the diffusion of vapor to any existing hydrometeors (including cloud water), the activation of new CCN, and vapor diffusion to the newly formed cloud droplets.

We devised a direct, non-iterative implicit algorithm for representing CCN activation and initial growth simultaneous with vapor and heat fluxes to larger ice and liquid hydrometeors, which permits long computational timesteps in RAMS. The method makes use of the ice-liquid potential temperature which is a prognostic variable and is conservative in both advective and vapor diffusional processes. The method also employs a pre-computed table of CCN activation numbers and droplet sizes based on integrations of a detailed cloud model run on a very small timestep for the duration of the longer timestep used in the dynamic model. This table is a function of five atmospheric parameters: temperature, two CCN activation parameters, dynamic supersaturation production rate, and fraction of CCN already activated. The two CCN activation parameters that are independent parameters of the table are C and

k in the well-known CCN activation equation

$$N = CS^k.$$

This formula gives the number N of CCN activated as a function of supersaturation S and of C and k, which are empirical properties of the local CCN population and depend on the number, size distribution, and chemistry of the CCN. The formula has been found to adequately describe cloud droplet activation in a number of laboratory and field studies and has been widely used. We construct the CCN activation tables by independently varying C, k, temperature, the number of CCN assumed to be already activated, and the dynamic production rate of S, and run a detailed model of vapor diffusional growth of newly activated CCN for each combination of the five parameters. Other parameters such as pressure were found to be of negligible importance in determining results of the detailed model and, hence, the table values.

In normal simulations in RAMS, values are accessed from the pre-computed tables to determine the number of newly activated CCN and the mass of water of newly activated cloud droplets each timestep. Initial tests of this scheme show the method to be computationally stable and to give realistic results. Results of the comparisons were presented at the IUGG conference in Boulder, CO, in July, 1995. However, unacceptably large discrepancies occur in some cases that we believe are related to the Eulerian, rather than Lagrangian, approach used in RAMS. We have decided to introduce Lagrangian parcel calculations in RAMS to correctly capture the activation phase of cloud formation. This is currently being implemented.

Once we found that the use of lookup tables enabled us to use more advanced physics computationally faster than with our old bulk microphysics algorithms, we decided to extend that approach to collection in which collection efficiencies could vary such as over the cloud droplet size-range. We realized that we were no longer constrained to use our woefully inadequate autoconversion routines. We then used a full bin model to more accurately represent the dependence of physical processes on hydrometeor size. The parts of the code in which this approach has been implemented are autoconversion of cloud droplets to rain, collection of cloud droplets by rain, and sedimentation. For autoconversion and accretion, 36 bins are employed to represent the entire liquid water spectrum, where each successive bin represents a doubling of droplet mass from the previous bin. These bins are filled with numbers of hydrometeors that correspond to the sum of the cloud and rain droplet gamma distribution size spectra assumed in the bulk model. Thus, the bins in general represent a bimodal spectrum with one peak in the cloud water size range and the other peak in the rain size range. Collision and coalescence rates are computed between each possible pair of the 36 bins, and new droplet sizes are evaluated by applying these coalescence rates for a short period of time. This results in a net loss of cloud total mass and number and a net gain of rain total mass and number. The rates of mass and number transfer are evaluated for a wide range of cloud and rain mass and mean diameter and pre-stored in a table. During model runtime, the mass and number transfer rates are accessed from the table in order to make the parameterization computationally efficient. Thus, the scheme combines the accuracy of a full bin computation with the computational speed of a bulk approach.

For sedimentation, 50 bins are used to represent different sizes from the hydrometeor spectrum. These bins represent a much closer resolution in size than a mass doubling as in autoconversion and accretion. The total mass and number in each bin from each grid cell are allowed to fall for a model timestep, and are then re-mapped to the grid cells that they

overlap. The total mass and number for each grid cell before falling are mapped onto new grid cells by summing over all bins. As done for autoconversion and collection, this mapping is computed before the model run for the necessary range of parameter space which includes hydrometeor mean size, atmospheric density (which affects fall velocity), and grid cell where the hydrometeors fall from on the given timestep. These values are entered into a table and efficiently accessed during a model run. A manuscript describing these developments was submitted for publication (Feingold et al., 1997).

2.3 A cloud-radiation parameterization scheme

Important to the simulation/prediction of a number of cloud systems such as fogs, stratus and stratocumulus clouds, cirrus clouds and Arctic stratus is the parameterization of the interaction of cloud hydrometeors with solar and terrestrial radiation. The radiation scheme is also important to the prediction of the diurnally-evolving cloudy boundary layer as it impacts the prediction of surface heat and moisture fluxes.

Harrington (1997) has developed a two-stream radiative parameterization scheme for both shortwave and longwave radiative heating. Our older cloud radiation scheme (Chen and Cotton, 1987) used an emissivity approach to parameterizing longwave radiation. This approach is fine in models with a few number of vertical levels, but for a cloud forecast model with, say, 50 vertical levels or more the costs of the scheme increase quadratically with the number of levels, whereas a two-stream scheme increases linearly with the number of levels. Moreover, the Chen and Cotton scheme responded to only the liquid water and ice water paths predicted by the microphysics model and not to the distributions of hydrometeors, particularly the existence of precipitation-sized particles. Some of the features of this scheme are as follows.

The new two-stream radiative transfer model interacts with model gases (H_2O, CO_2 and O_3) and cloud hydrometeors. Gaseous absorption uses fits to gaseous transmission data for 3 solar and 5 infrared bands following the method outlined in Ritter and Geleyn (1992).

Cloud optical properties are derived such that correspondence with the different RAMS microphysical models is achieved. The optical properties for the bulk microphysical parameterization (Walko et al., 1995) are derived for the assumed gamma distribution functions, for liquid water drops following the modified anomalous diffraction theory of Mitchell (1997), and for various ice crystals following Mitchell and Arnott (1994). Optical properties are computed for each model band, for both the liquid and ice particles, which are then fit as a function of the characteristic diameter, D_n, of the distribution function. The fits produce little error and allow quick computations of the optical properties over a given band.

Optical properties for the bin microphysical models (Feingold et al., 1994 and Reisin et al., 1996) are derived by producing mean coefficients for each bin and then appropriately summing. Liquid water drops use Lorenz-Mie theory for the computation of the optical properties while the ice microphysical model utilizes the method of Mitchell and Arnott (1994). Computations with idealized gamma distribution functions show that this method produces excellent accuracy. The largest errors (2%) occur for distributions highly peaked within the smallest microphysical bin, however this rarely happens.

This scheme has been applied to the simulation of warm-season Arctic stratocumulus clouds (Olsson et al., 1997a,b), transition-season Arctic stratus clouds (Harrington et al., 1997), marine boundary layer clouds (Stevens, 1996), and recently to the simulation of mid-latitude and tropical cirrus clouds.

2.4 Forecasting Arctic Stratus Clouds

2.4.1 Summer-season ASC

The radiative transfer model was then used to improve simulations of ASC which are strongly dependent upon radiation to drive the dynamics (e.g. Curry 1986). Since accurate simulations of ASC require accurate modeling of the drizzle process (Olsson et al., 1998), an explicit (binned) representation of the droplet spectrum was utilized (Stevens et al., 1996a). Since the droplet spectrum can evolve freely within this microphysical representation (i.e. a distribution function is not assumed *a priori* as in the Walko et al., 1995 model), cloud optical property routines were developed to take advantage of this feature (Harrington, 1997). Simulations using this method, compared to simulations using the gamma distributions showed the importance of accurate computation of the radiative properties of the cloud to the evolution of the cloud layer dynamics (Harrington, 1997).

2.4.2 Radiative impacts on droplet growth

Since an accurate coupling of an explicit microphysical model to a radiative transfer model had been accomplished, studies of how radiative heating and cooling can affect the vapor depositional growth of droplets was carried out. This effect may be important for determining the onset of precipitation from stratus and stratocumulus cloud layers because cloud-top radiative cooling will enhance the vapor growth rate of cloud drops. This could speed up the time for cloud drops to gain sufficient size (about $25\mu m$ in radius) so that collision-coalescence can produce precipitation-sized drops. In a like manner, solar heating of a cloud layer will suppress the growth of drops, thus reducing drop growth.

Two modeling frameworks were used to study this effect (Harrington et al., 1998a). The first model is a trajectory ensemble model (TEM) which was successfully utilized by Stevens et al. (1996a) to study the microphysical structure of stratocumulus. This model takes as input data from 500 parcels which follow the cloud-scale motions within a RAMS simulation of a stratus cloud. We utilized a simulation of ASC as our test-bed and wrote out thermodynamic, dynamic, and radiative data from a RAMS simulation. This model has some advantages over a full RAMS simulation in that numerical effects such as spurious cloud top supersaturations do not occur (Stevens et al., 1996b). However, the method does not include other factors such as subgrid-scale motions that could affect the results.

The TEM analysis shows that the radiative effect reduces the time required for the onset of drizzle by up to 30 minutes in some cases, depending upon the cloud-top residence time of the parcels. This is also shown to depend weakly on the inclusion of SW heating but more strongly on the size of the activated drops. When parcels spend at least 12 min at cloud top, drop spectra develop bimodality, which has been shown to be due to the fact that drops with $r < 10\ \mu m$ evaporate. This is shown explicitly in Fig. 1; note the production of not only a drizzle-drop mode but also a smaller mode with time. Large drops are not necessary for this mechanism to act; in fact simulations without collection also show this feature. This differential growth characteristic also appears, with a similar $r \simeq 10\ \mu m$ delineation size, in the ensemble TEM results. The rapid decrease in Q_{abs} for drops with $r < 10\ \mu m$ is suggested as the reason for this behavior.

Results using the ensemble TEM calculations (i.e. using all 500 parcels and examining statistics) show that drizzle production is predominately confined to the large LWC regions near cloud top, and that this is strongly increased by including the radiative term. However,

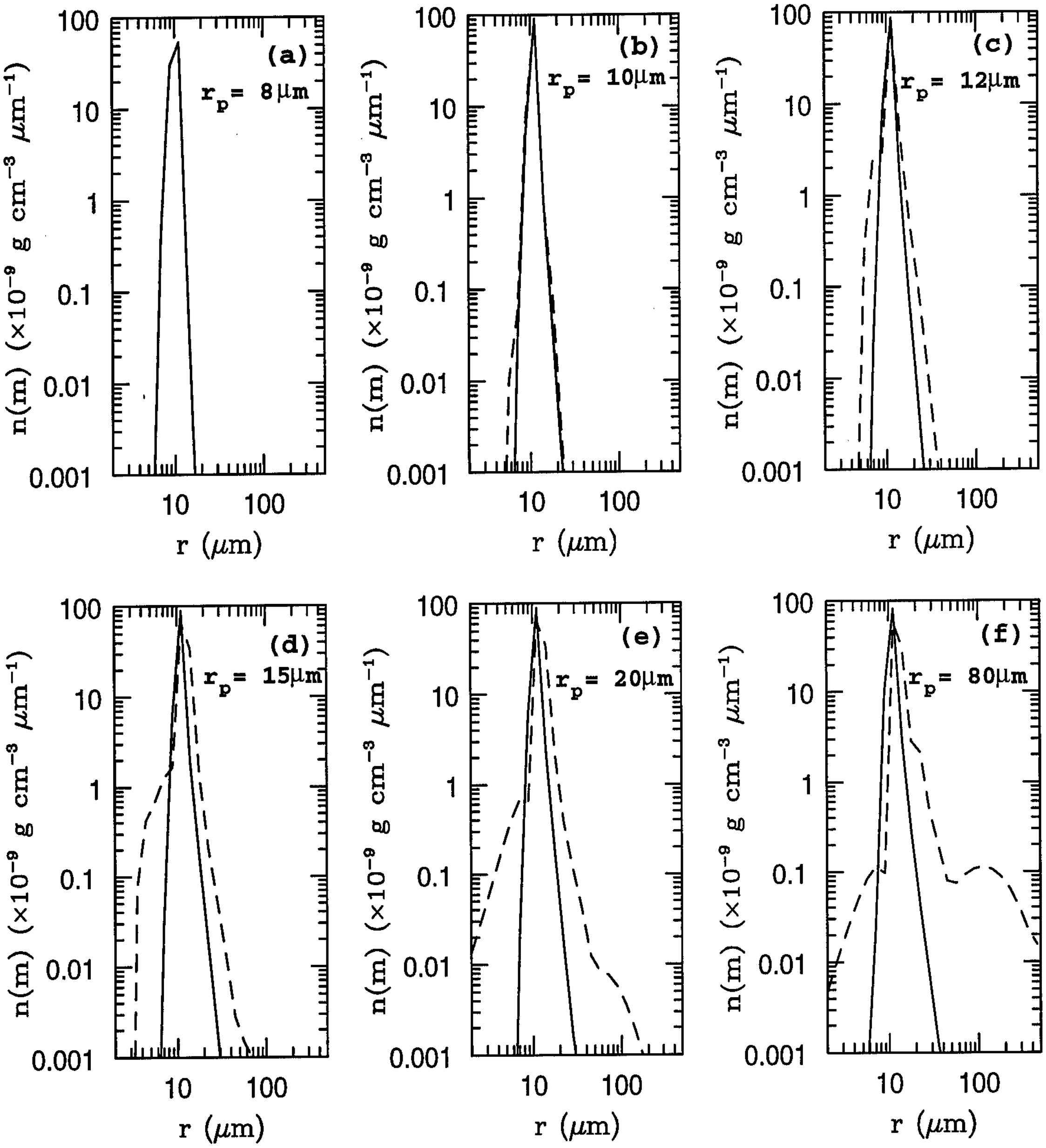

Figure 1: Time-series of the mass-distribution function of drops as a parcel traverses cloud top. Panel (a) is for 4.1 hours, (b) is for 4.2 hours, (c) is for 4.4 hours, (d) is for 4.6 hours, (e) is for 4.8 hours and (f) is for 5.0 hours. The dashed line and solid line are for runs with (TAP) and without (TNR) radiation, respectively. Values of r_p are given in the plot.

plots of drizzle mass fraction as a function of cloud top residence time (t_c) show that the radiative term increases drizzle mass in parcels that contribute to drizzle without the radiative effect. In other words, the radiative effect did not produce copious increases in drizzle amounts within parcels that have shorter cloud top residence times. Of course, parcels with lower t_c values are more numerous and, therefore, it seems logical that shifting drizzle production to smaller t_c should enhance drizzle amounts. Although this did not occur through the radiative term alone, activation of a few large-sized CCN did cause a shift of drizzle production to smaller t_c. In this particular case, it was shown that the large CCN activation was the cause of the shift to smaller t_c and not the radiative term. Calculations with larger CCN concentrations showed that drizzle suppression was due to the fact that few parcels have long enough cloud top transects to initiate drizzle production.

The simulations within the RAMS framework showed small differences between the cases with the radiative term and those without it. Drizzle onset appears to occur between 12 and 30 minutes earlier with the radiative term, however the simulation without the radiative effect quickly caught up. Simulations with larger CCN concentrations show a similar effect. However, one must keep in mind the greater complexities of CRMs when examining such a phenomenon within the framework of an Eulerian model that predicts supersaturation. Such models are subject to advective and diffusive broadening of the drop spectra (e.g. Clark, 1974; Stevens et. al., 1996a). In addition, and perhaps most importantly, the drop growth equations are forced by the supersaturation field. Thus, the spurious production of cloud-top supersaturations which occurs in Eulerian models (Stevens et al., 1996b) will mask the results of calculations with time. These results are shown in Fig. 2; note that, in time, the differences between the simulated drop spectra are not as great as in the TEM. Because of these effects, it is difficult to say much, with confidence, about exactly how radiative heating and cooling effects on droplet vapor deposition might impact drizzle in a dynamically-coupled model.

2.4.3 Mixed-Phase Arctic Stratus Clouds

Little is known about Arctic cloudiness in general, and this is especially true of mixed-phase (e.g. water and ice phase) clouds in the arctic during fall, winter and spring . The arctic region is understood to be potentially susceptible to climate change events (Curry et al., 1996). However, the strength of climate-arctic system feedbacks are strongly connected to cloud cover amount (Curry et al., 1993) and cloud composition (Curry et al., 1997). Mixed-phase clouds, which occur over the arctic during fall and spring, appear to have an impact on the subsequent freezing and thawing of the ice pack (Curry et al., 1997). Since mixed-phase clouds are colloidally unstable (i.e. ice crystals rapidly grow in size at the expense of liquid drops and, hence, precipitate from the cloud layer), understanding the maintenance of mixed-phase layers over the arctic in fall and spring is crucial to understanding the arctic system.

We used the RAMS model with an explicit (binned) representation of the cloud droplet and ice crystal size spectra (Reisin et al., 1996) coupled to the two-stream radiation model (Harrington et al., 1998b) in order to simulate mixed-phase ASC that would occur over the ice pack during fall. Since little data are available for these cloud systems, we created a physically plausible situation by cooling our summer ASC soundings in 5°C increments, thus producing a mock transition.

Figure 3 shows a shaded contour plot of the last 4 hours of an 8 hours simulation of a mixed-phase ASC cloud layer (the sounding was cooled by 5°C). Note that the cloud layer

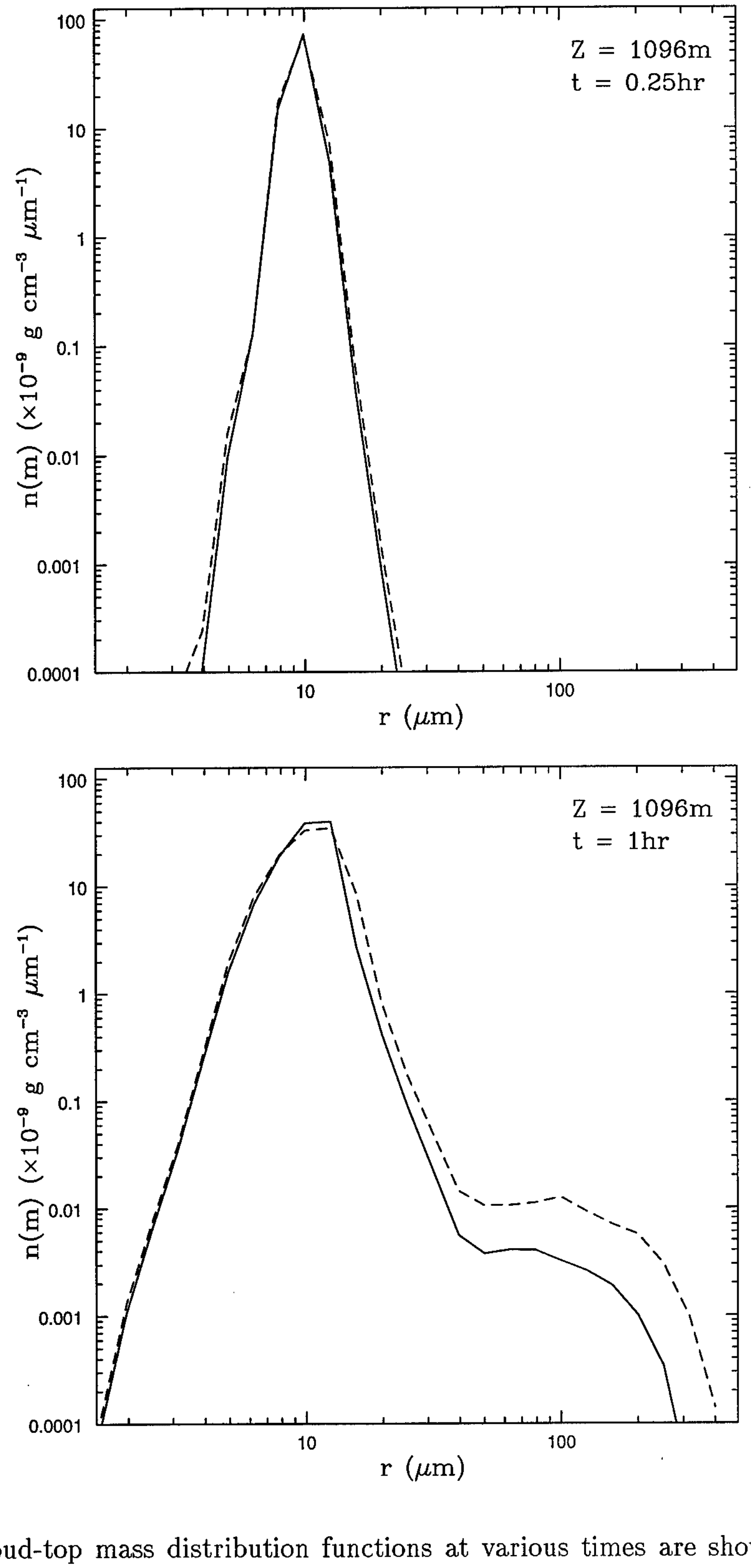

Figure 2: Cloud-top mass distribution functions at various times are shown. Simulation without radiative effects is denoted by the solid line while the simulation with radiative effects is denoted with the dashed line.

undergoes rapid glaciation at 19:00 hours followed by a period of approximately constant ice production within the cloud layer which is removed through precipitation processes. The cloud layer is able to maintain itself against collapse because the ice crystals are removed by the precipitation process. Thus, after the period of glaciation, the ice crystal concentrations are strongly reduced within the cloud layer. Because of the strong precipitation from the cloud layer, the layers beneath the cloud are cooled and moistened over only a short period of time. This leads to a much more stable layer beneath the cloud. These simulated characteristics have been observed during the Beaufort Arctic Sea Experiment (BASE) conducted in 1994 (Pinto, 1998).

Large coolings (10°C) cause increases in nucleated ice concentrations and more rapid growth rates of the ice crystals. This causes rapid collapse of the cloudy layer as is shown in Fig.4, thus corroborating the importance of temperatures and ice concentrations in the production of stable mixed-phase cloudy layers. Sensitivity experiments conducted to illustrate these impacts show that significant reductions in ice nuclei concentrations at cold temperatures must be realized if a cloud layer is to remain stable. In addition, if ice growth produces an ice crystal shape that has a larger terminal fall speed, larger ice concentrations can be realized because the ice is removed from the cloud layer at a much more rapid rate.

In addition to the above, we have also shown that rapidly precipitating mixed-phase cloudy layers can initiate layer formation in the arctic. While it has been known for some time that layered ASC are a common feature over the arctic, the physical reason for the layered formation has not been completely explained. Indeed, differing explanations exist and it appears likely that each occurs in the arctic (Curry et al., 1996). Figure 5 shows the last 4 hours of an 8 hour simulation in which ice concentrations in the 5°C cooled sounding simulation are doubled. Not only does this show that increases in ice concentrations reduce the stability of the cloudy layer (compare this with Fig. 3), but it shows that a lower cloud layer is formed after about 1.5 hours. The lower liquid cloud layer is formed through a process whereby the ice crystals precipitating from the upper cloud deck cause a lower level moisture inversion through sublimation (moistening and cooling). Once the upper cloud deck has become optically thin, the lower moisture inversion can cool in the infrared. Eventually, water supersaturations are realized and droplets activate forming the lower layer. This cloud layer is maintained by continued radiative cooling.

2.5 Forecasting cirrus clouds

2.5.1 Extratropical Cirrus

A major focus of our AFOSR-sponsored research has been to improve prediction of cirrus clouds. The RAMS mesoscale model with interactively nested grids was used by Ting Wu to simulate the 26 November 1991 FIRE II cirrus case. Mesoscale nested grid simulations with three and four grids have been completed. The first simulation with four nested grids (grid spacings are: 80 km, 20 km, 4 km, 1 km) was set up to study the weaker part of the observed cloud system. This part consisted of a weaker and shallower cloud layer to the south-southeast of the main cloud system. By doing so, the mesoscale structures of the shallow cloud layer were well resolved by RAMS.

The other simulation with three nested grids (grid spacings are: 80 km, 20 km, 4 km) was set up to study the main cloud system which was to the northwest of the shallower cloud layer. Observations showed that the main cloud system had large high-cloud optical depths

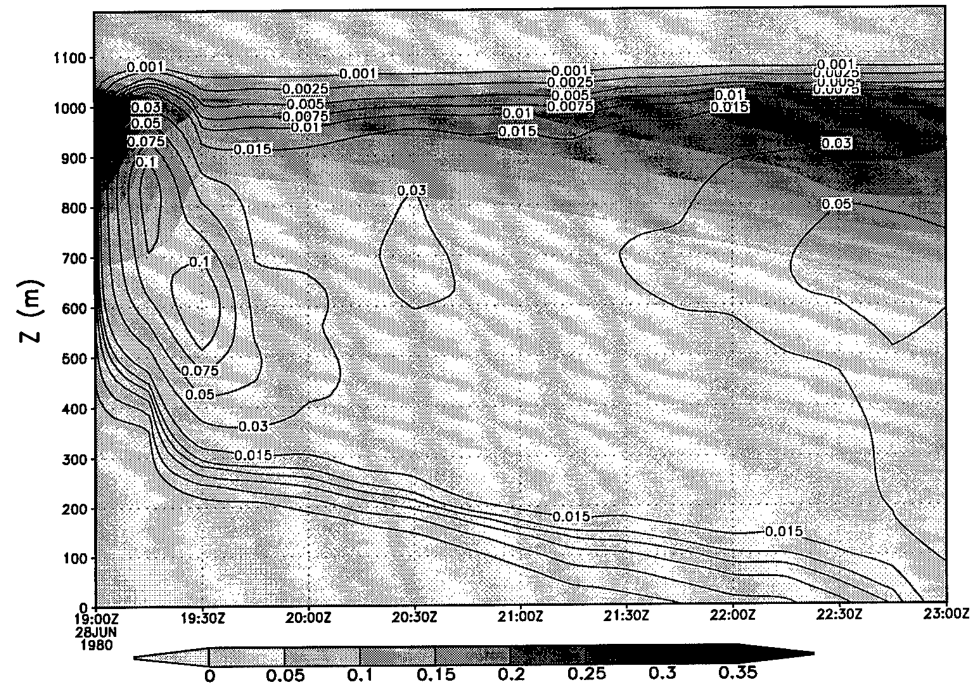

Figure 3: Time Series: LWC (shaded) and IWC (contoured) in g m^{-3} for 5°C cooled simulation.

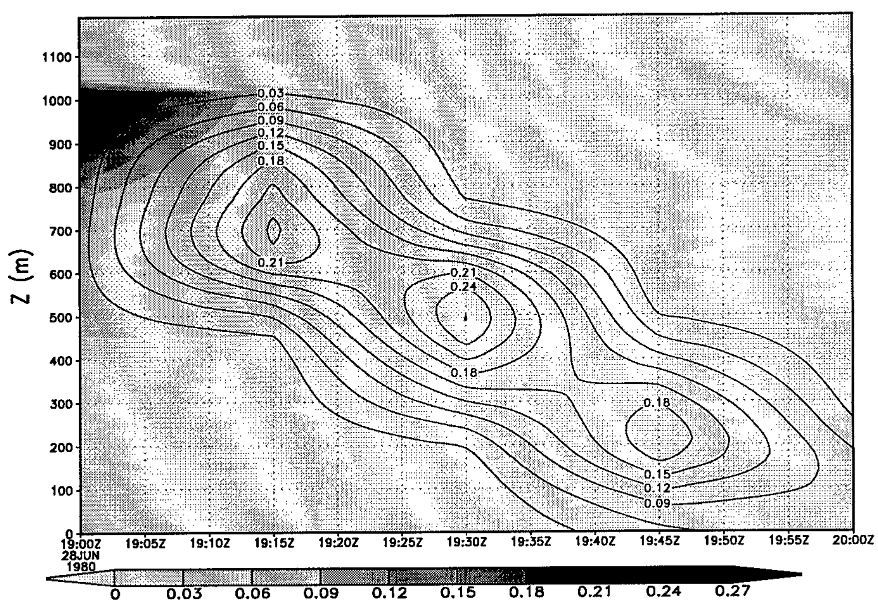

Figure 4: Time Series: LWC (shaded) and IWC (contoured) in g m^{-3} for 10°C cooled simulation.

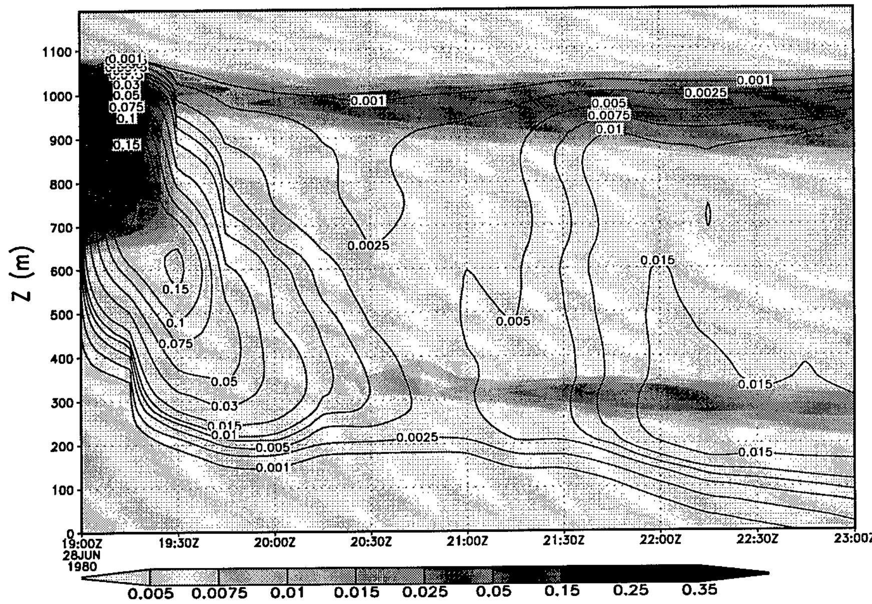

Figure 5: Time Series: LWC (shaded) and IWC (contoured) in g m^{-3} for 5°C cooled simulation with doubled ice concentrations.

which was believed to be caused by thick cloud layers underneath the highest layer. This simulation was intended to evaluate the model performance when the model is used to predict the middle latitude deep layered ice cloud.

Simulations over a 24 hour period predicted nearly identical synoptic circulation to the MAPS analyses. The model also produced a cirrus cloud macrostructure that was comparable to the satellite and ground-based remotely sensed cirrus observations for the day (Mace et al., 1995; Minnis et al., 1993; Intrieri et al., 1995; Gultepe et al., 1995). Thin cirrus was simulated over the Coffeyville, Kansas, while thicker cirrus was simulated in a southwest to northeast-oriented band further to the west. Simulated ice water contents over Coffeyville were about $0.03 g/m^3$ while observed values were as high as $0.04 g/m^3$. The dominant vertical motion in the weak cirrus band was predicted as about 4-6 cm/s which was comparable to the observed mesoscale vertical motion of about 6 cm/s.

While the mesoscale simulations have been encouraging, CRM simulations are necessary to further our understanding of the dynamics of middle latitude cirrus clouds. The model for CRM studies inherits the framework of RAMS version 3b. However, it includes Harrington's (1997) cloud-interactive two-stream radiation scheme. It also includes a new subgrid scale model developed by Kosovic (1996) at the University of Colorado.

The subgrid-scale (SGS) model represents a critical component of a successful cloud resolving model simulation. The commonly used linear SGS models result in erroneous mean velocity profiles in simulations of neutrally and stably stratified atmospheric boundary layers. In addition, linear models are absolutely dissipative resulting in relaminarization of the flows subjected to strong stable stratification. Since cirrus clouds in the midlatitude are generally associated with stable stratification and strong wind-shear Kosovic's SGS model, which is

capable of reproducing the backscatter of energy as well as the effects of SGS anisotropy characteristic for shear-driven flows, is more suitable for this study.

For this research, since the CRM study is an extension of the mesoscale modeling studies, information from the mesoscale simulations is communicated with the CRM studies as much as possible. A nudging algorithm is used in which the mesoscale simulation outputs are used to drive the CRM.

The cloud resolving model was initialized using soundings taken from the third grid of the mesoscale simulations. A much finer grid mesh was used: $\Delta x = \Delta y = 100m$. Δz was used as a variable ranging from 50 (within the cloud layer from 6 to 10 km) to 400 m (near the surface). The model had a horizontal domain of 18 km and a vertical domain of 12.4 km (120 vertical levels).

Two 2D-simulations were performed. The first one was initialized with a sounding extracted from the weaker portion of the observed cloud. This simulation was expected to predict the small-scale activity (which can not be effectively resolved by mesoscale models) within shallow cirrus clouds. The second simulation was initialized with a sounding extracted from the deeper main cloud system and expected to resolve the activity within middle-latitude deep layered ice clouds.

After two hours into the simulations, the second simulation predicted deeper clouds (from 2.2 km to about 11.0 km above the ground) with several layers, rather than a single-layered cloud from 4.0 km to about 10.7 km above the ground as in the first simulation. The predicted maximum snow concentration, snow mixing ratio, pristine ice concentration, and pristine ice mixing ratio were 36 l^{-1}, 0.068 gkg^{-1}, 10.2 l^{-1}, and 0.00119 gkg^{-1}, respectively, for the second simulation, while the corresponding values for the first simulation were 31 l^{-1}, 0.09 gkg^{-1}, 32 l^{-1}, and 0.0032 gkg^{-1}

2.5.2 Tropical Cirrus

For the modeling of tropical cirrus clouds, Cristian Mitrescu (1998) has concentrated on the TOGA COARE case of December 21^{st}—December 25^{th} 1992. This is the case that GCSS Working Group #4 has concentrated on for a model intercomparison study. Since RAMS has been run as a deep convective CRM for this case we decided to use the simulated cirrus resolved with 1.0 km grid spacing as the initialization data to drive a high-resolution CRM of tropical cirrus clouds. This simulation uses both the two-moment microphysics and the new cloud-interactive two-stream radiation scheme.

Two distinct runs were performed: one in a three–dimensional configuration and one in a two–dimensional configuration. Because of its complexity and flexibility, RAMS was able to successfully simulate a cirrus cloud that has all the physical properties close or very close to those that were measured and/or produced by other models. And its new two–stream radiation module makes it more accurate because it takes into account individual hydrometeor species distribution parameters. In the set–up for these simulations a relatively small grid space was used: 100 m for horizontal grid spacing and as low as 50 m for most of the vertical grid spacing. Since the focus was to describe cirrus clouds, out of seven possible hydrometeors species only four were allowed: cloud droplets, pristine ice, snow and graupel along with water vapor.

The three–dimensional simulation proved realistic: it predicted a stable thick cirrus cloud with base around 8000 m and top at 11200 m. Below this layer, separated by a dry layer,

another layer consisting mostly of aggregates was present. As first noted by *Stevens (1996)* these layers were coupled in the presence of internal stratification.

Mixing ratios for the ice crystals predicted by the model were in the limits of the measurements made in the tropical cirrus. Both layers showed a layered structure which is consistent with observation made with lidars.

As other studies pointed out before, it was shown that in tropical cirrus clouds the turbulence is bi–dimensional in nature and the main source for producing it is due to buoyancy term.

The heating rates, which are very important in the dynamics of a cirrus cloud and influences the microphysical processes, were in the relatively large limits measured. But as noted by Zender and Kiehl (1994) significant changes in heating rates can be due to small changes in the absorption properties of a given distribution of hydrometeors, which are not very well measured for the tropical cirrus and also display a large variability.

As stated before, another goal of this research was to determine analytical expressions for the probability distribution function (PDF) for the vertical velocity. This PDF can be used in the one–dimensional models to improve their microphysical performances. The study show that a Gauss distribution function is a very good and simple approximation, since it requires only two measurable parameters: mean and variance of the vertical speed.

The two–dimensional run produced very similar results as the three–dimensional one, but slightly higher values. This may be due to the fact that the meridional influence near the equator is very small along with the fact that the Coriolis force is negligible. Another reason for this may be the fact that for both runs the nudging variables were obtained from a two–dimensional run of RAMS set up as a CRM.

2.6 A Global, Interactive Nested Grid Cloud Forecasting System

RAMS is designed with the option to operate in stereographic coordinates on scales up to hemispheric. Because of this feature, it is a relatively simple matter to adapt RAMS as a global model. The essential requirement is to develop an interface between the two hemispheres. This is accomplished with the existing nesting algorithms is the model; one hemisphere is treated as a nested grid of the other hemisphere. A specific complication of this approach to globalizing the model is that the geographical coordinates of the Arakawa C-grid points of one hemisphere will not coincide with the geographical coordinates of the grid points on the other hemisphere. Consequently, interpolated values from one grid must be imported to the other grid with every time step. For scalar quantities this requires that the four grid points surrounding (in geographical space) the projected location of a grid point from the other hemisphere must be identified so that a simple bilinear interpolation may be done. For u- and v-components, however, four u-points and four v-points must be identified for each. The points used in each interpolation are determined initially and then stored in a look-up table, while interpolations are done each time step. For the vector quantities, transformations are accomplished using the existing RAMS algorithms for converting polar stereographic components into spherical components and then converting spherical components back into the polar stereographic components appropriate to the other hemisphere. A simpler, less computationally expensive approach that may be included in refinements to the global model would be to do the transformation of vector quantities directly between the two hemispheres. Browning et al. (1989) have used this two-hemisphere stereographic approach with good results.

The hemispheric interfacing algorithms of global RAMS have been tested with several imposed wave patterns in the global potential temperature fields. Three- and four-wave patterns are established on otherwise globally homogeneous fields and the evolution of the potential temperature, Exner function (non-dimensional pressure), and wind fields is observed. These simulations are essentially "reverse dishpan" experiments, in that the wave pattern is specified and allowed to run down in the absence of radiative forcing. The intent of these is not to draw any conclusions concerning atmospheric motion, but simply to produce a field in motion and then determine the amount of noise generated around the interface. These simulations were run for 15 vertical levels on 50 X 50 grid domains representing each hemisphere. The tangent points of the antipodal hemispheric stereographic grids were placed at the geographic poles, on the equator, and at latitudes in between. In all of these simulations, noise around the great circle common to both hemispheres was virtually non-existent.

Current versions of RAMS are formulated with quasi-Boussinesq equations of motion. The Boussinesq assumption is not appropriate for a global model, and so a fully non-Boussinesq equation set must be included in global RAMS. Such a system has already been developed and used with success by Tripoli (1992) for the University of Wisconsin mesoscale model. These equations are written in an enstrophy conserving form, rather than the traditional scalar momentum forms to which the Boussinesq approximation is applied. Instead of taking a scalar advection form, the enstrophy form views the velocity tendency as a set of dynamic balances between inertial, pressure gradient, and gravitational forces. Rotational accelerations (including Coriolis) are grouped into a single term while inertial forces are treated as a kinetic energy gradient. Because of the similarities between this model and RAMS, this would be the most appropriate approach for the global version. These non-Boussinesq equations will be included in the model within the next several weeks, at which point the initial version of global RAMS will be ready for testing with realistic case studies. The first tests of global RAMS will involve investigations of the interrelationships between bursts of tropical convective activity associated with El Nino and the intensities and trajectories of extra-tropical cyclones.

2.7 Parallel-processing version of RAMS

In recent years two parallel-processing versions of RAMS has been developed. One version was developed by Jim Edwards while a CSU employee in cooperation with the Scalable Modeling System being developed at the Forecast Systems Lab (FSL) of the National Oceanic and Atmospheric Administration (NOAA). The parallel system is designed so that it can run either on high-performance massively-parallel computers or on inexpensive clusters of workstations that can be easily transported and maintained in a field application. This effort culminated in the 1996 Summer Olympics Weather Support Project. In this project a 30 node IBM SP-2 parallel computer was installed in the Olympic Weather Support office in Peachtree City, Georgia. After an initial debugging period the entire forecast modeling process, from receiving initial and boundary data from the National Center for Environmental Prediction (NCEP) to producing two and three dimensional graphics for use by the forecasters, was automated. RAMS was run in three hour cycles and with horizontal grid spacings of two or eight kilometers. The 8-km model produced a 24-hour forecast over the entire state and the forecasters had control over choosing the location of the 2-km grid.

The second version was begun by Craig Tremback, while a CSU employee, and continued while working at Mission Research Corporation. Bob Walko, a CSU employee on this project

has collaborated with Tremback in developing this version. This version is also designed to be run on MIND architecture and shared memory systems. After comparing and testing these separate parallel-processing versions of RAMS we have decided to support the MRC version at CSU because we have found it to be faster and more flexible in terms of the number of computer nodes it can work with. This version has been implemented on a six-processor inexpensive cluster of IBM RISC workstations and is providing forecasts for the Colorado, Southern Wyoming and Eastern Utah areas. This is a two grid nested version of RAMS that provides us an excellent laboratory to test out our cloud forecasting algorithms in a realtime setting year around.

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5 Publications Supported

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6 Interactions/Transitions

The cloud microphysics and radiation parameterizations developed under support of this grant are being used at a number of research organizations and universities. The host model, RAMS, is being used at over 40 universities, research organizations, and operational forecast centers worldwide.

Mission Research Corporation is also applying RAMS to various military activities including those by Kennedy Space Center and Defense Nuclear Agency. Several AFIT students trained in RAMS are now working at various Air Force bases.

7 New Discoveries, Inventions, or Patent Disclosures

NONE

8 Honors/Awards

Dr. William Cotton is a Fellow of the American Meteorological Society and a Centennial Fellow of The Pennsylvania State University.